

Arroyo Center

Vertical Envelopment and the Future Transport Rotorcraft

Operational Considerations for the Objective Force

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PREFACE

This report summarizes the research findings of an Arroyo Center analysis of the risks and uncertainties associated with developing a Future Transport Rotorcraft (FTR) to help fulfill a vertical envelopment mission for the Objective Force. In this concept, the FTR would move new medium-weight armored vehicles, known as the Future Combat Systems (FCS), about the battlefield and across enemy air defenses. The findings should be of interest to defense policymakers, military technologists, and concept developers.

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SUMMARY

BACKGROUND

The Future Combat Systems (FCS) as envisioned by the Chief of Staff of the Army, General Eric Shinseki, is a rapidly deployable, medium-weight family of combat vehicles that will have the lethality of today's heavy armor forces. Survivability will be achieved by a combination of new technology, enhanced vehicle mobility, and new concepts of operations. One concept uses rotorcraft to rapidly transport the FCS force around the battlefield. The use of heavy lift rotorcraft to "vertically envelop" the adversary with the FCS force package has shown significant promise in wargames and simulation models. This vertical envelopment concept has been of particular interest to planners considering options for the Objective Force, the mobile Army force structure that will emerge after 2010.

While theoretically attractive, the vertical envelopment concept places significant demands on any aircraft that could transport the FCS. Although the actual designs are yet to come, Objective Force planners have set initial nominal design specifications for FCS and the Future Transport Rotorcraft (FTR). Current design goals are for the FCS to weigh less than 20 tons, and for the FTR be able to execute 500-kilometer, round-trip FCS transport missions in an all-VTOL (vertical takeoff with payload, vertical landing with payload) mode. The FTR will be sufficiently robust to move freely about the battlefield with a minimum of limitations imposed by survivability concerns.

FTR CRITICAL ISSUES

The key FTR issues are the technical risk, cost, and survivability of the FTR both at the nominal parameters and at variations from those values. Senior policymakers have expressed interest in understanding the location of the “knee of the curve”—the point at which the technical challenges and uncertainties begin to grow and produce diminishing performance benefits—for each of these issues. Our primary goal was, therefore, to identify the knee in the technical risk versus performance, cost versus performance, and survivability versus threat curves. Our secondary goal was to put the study results in the context of implications for a potential Army Integrated Concept Team (ICT). The ICT is the first formal stage of the weapon acquisition process. When this study was completed in 2001, the Army’s Aviation School at Fort Rucker, Alabama, was poised to conduct the ICT but was unable to obtain the funding to initiate this effort.

ORGANIZATION OF THIS REPORT

Chapter One describes the overall FTR concept and the issues of development costs and technical feasibility with today’s technology. We show that the FTR would significantly exceed the payload-radius capabilities of today’s large rotorcraft. However, we also show that the modernization of existing rotorcraft with new, but flight-proven, subsystems might allow the transport of lighter weight FCS vehicles (about 12–15 tons) over distances within a 100-kilometer radius. Achieving 20-ton lift capability requires a new advanced transport aircraft start, with a \$10–20 billion development cost. Thus, the transport of 12- to 15-ton FCS vehicles over modest distances is one representation of the knee in the cost versus performance curve

Chapter Two reviews the impact of advanced rotorcraft technology on the feasibility (technology readiness levels) and cost of the FTR. New technology is needed to lower the weight of the FTR, which is assumed, at this preliminary point in the design process, to be a surrogate for cost. We discuss the use of weight in this manner and highlight some concerns about the validity of this metric. Assuming the relevance of the weight metric, we also show that bringing FTR costs down to historical patterns for rotorcraft (roughly 1.5 times the cost of comparable-load, fixed-wing aircraft) will require a significant

acceleration, beyond historical trends, of technical progress. We also show that there are significant uncertainties about translating that progress into cost reduction. While there is not an official cost number beyond which the FTR is unaffordable, program production costs in the tens of billions would appear to represent a knee in the affordability versus performance curve.

Survivability is discussed in Chapter Three. We used the RAND air defense simulation model to show that FTR attrition rates approach acceptable levels only under conditions of extensive suppression of enemy air defenses (SEAD), either by other aircraft, or by onboard IR and RF missile countermeasures (IRCM and RFCM). Additionally, high pilot situational awareness of the location of the air defense assets, along with stealthy FTR signatures, will be critical for FTR survivability against anti-aircraft artillery (AAA). We also describe how, historically, hand-held IR surface-to-air missiles (SAMs) have quickly developed countermeasures to each new generation of IRCM systems. These SAMs and other low-altitude air defense weapons are available to virtually any military force in the world, with cost being the only limitation. We conclude that major new defenses against IR and RF guided missiles, along with an AAA countermeasure development program, will be required for the FTR to have freedom of movement on the battlefield. The program has both significant cost and technical risks. Without an aggressive and successful survivability program the FTR will have significant operational limitations.

STUDY FINDINGS

Information used in this study was current as of July 2001. We have three principal findings from this study, which are summarized in Table A.1.

Cost. The first finding is that an FTR designed to carry a 12- to 15-ton payload on a 100-kilometer round trip, and flying around the battlefield rather than through it, offers vastly reduced cost and minimizes technical risks compared to an FTR meeting the nominal requirements.

Technical risk. Our second finding is that the FTR has significant technical risk. The Army science and technology (S&T) community is assuming that the pace of progress will exceed historical patterns. While progress at the component level has in certain cases exceeded

Table S.1

Summary of Study Findings in the Areas of Cost, Risk, and Survivability

	Development	Production	Knee in the Curve
Cost	Current technology supports a 12- to 15-ton payload, 100-km combat range rotorcraft. New start required for rotorcraft. RDT&E: \$10–20 billion.	Even with optimistic technology projections, FTR per-unit flyaway costs over \$100 million vs. \$30–40 million for modified CH-53E.	New start: \$10–20 billion; CH-53E mod: \$200 million.
Technical risk	Basic research needed for quad tiltrotor. Ambitious goals for development of FTR engine, blade, and transmission.	TRLs sufficiently low resulting in uncertain manufacturing and maintenance costs.	TRL 3 for quad tiltrotor, 3–4 for dual tiltrotor, 5 for helicopter.
Survivability	Can counter 1st and 2nd generation IR SAMs, ballistic protection up to 25mm AAA.	Both new onboard and offboard IRCM and RFCM needed. Tiltrotor flight profile lower risk.	Current technology sufficient for low-end SAM threat. AAA threat problematic. Large developmental effort needed for current high-end threat.

historical patterns, it has not done so for some of the critical major subsystems (rotors/ blades, for example). The major technical risks, as opposed to feasibility (i.e., an FTR can be built, but at great expense), are that the time and development costs of the FTR will, in our estimation, be greater than is acceptable for the Objective Force planners. We therefore recommend that the Army S&T community work closely with the operational community and establish more modest goals that would still allow development of a militarily useful system.

Survivability. A significant component of the technical risk is survivability of the FTR. Our third finding is that the FTR will require a multibillion-dollar survivability enhancement program. Indepen-

dent of aircraft type, the requirement to land in enemy territory presents a major survivability design issue. Our analysis indicates that both conventional missile jammers and unconventional hard kill technologies must be developed to give the FTR the ability to survive on the battlefield. Current funding is insufficient to develop the technology in a timely fashion. Survivability equipment may increase aircraft weight by as much as 2 to 5 tons.

The vertical envelopment concept is sufficiently attractive that the Army should continue to consider its feasibility, but the Army must also realize that achievement of the nominal technical parameters is an ambitious and risky goal. The tradeoff space involving mission performance and FTR requirements, however, has not been fully explored. It is too early to focus on a point design for FTR or even exclusively on a VTOL solution. The development and acquisition community must continue and expand its interactions with force planners, modelers, and strategists if an affordable and militarily viable FTR is to be built.

ABBREVIATIONS

AAA	Anti-aircraft artillery
ADA	Air defense assets
AMRDEC	Aviation and Missile Research, Development, and Engineering Center (Army)
APC	Armored personnel carrier
ATD	Advanced technology demonstration
DEW	Directed Energy Weapon
DIRCM	Directed Infrared Counter Measure
FCS	Future Combat Systems
FLOT	Forward line of troops
FTR	Future Transport Rotorcraft
HMG	Hand-Held Machine Gun
HOGE	Hover out of ground effect
ICT	Integrated Concept Team
IRCM	Infrared countermeasures
JTAGG	Joint Turbine Advanced Gas Generator
LAV	Light Armored Vehicle
MANPADS	Man Portable Air Defense System
NASA	National Aeronautics and Space Administration

RDT&E	Research, development, test, and evaluation
RFCM	Radio frequency countermeasures
RJARS	RAND's Jamming Aircraft and Radar Simulation
RPG	Rocket-propelled grenade
S&T	Science and technology
SA	Situational awareness
SAMs	Surface-to-air missiles
SEAD	Suppression of enemy air defenses
TRADOC	Training and Doctrine Command
TRL	Technology Readiness Level
VTOL	Vertical takeoff and landing

INTRODUCTION

This report presents an analysis by the RAND Arroyo Center of the use of large rotorcraft to accomplish a vertical envelopment mission for the Army's Objective Force. This study was completed in 2001 with a cutoff date of July 2001 for information used in the research. The term "Objective Force" refers to the Army's plans for a lighter, more maneuverable force to be deployed in 2010 and beyond.

An often-discussed concept for the Objective Force is the medium-weight family of armored vehicles known as the Future Combat Systems (FCS). The FCS is not yet defined, and there are highly varied visions of it. More conventional opinions envision the vehicle type as "light tank," while others see the FCS as a "system of systems" that is highly modularized, with different configurations possible for different capabilities.

Although the detailed design and operational concepts of the FCS remain under study, the Army envisions itself as proceeding through a transformation that will result in a lighter, more deployable Army. Part of that vision contains the widespread assumption, bolstered by the Army Chief of Staff, that the major systems in the Army must be deployable in a C-130 transport aircraft. The C-130 can lift 20 tons under some circumstances, resulting in a working assumption that the FCS vehicles would have to be lighter than 20 tons.

Recently, military planners have shown great interest in transporting the FCS to and within the battle site on a rotorcraft. This would vastly increase the speed and versatility of the FCS. However, a 20-ton FCS would exceed the payload capabilities of modern transport rotorcraft. Correspondingly, there has been enthusiasm in both the

FCS and rotorcraft communities for a new rotorcraft that might be able to manage such loads over useful ranges.

Figure 1 shows a simple schematic of the vertical envelopment mission. It also highlights the nominal requirements that have been discussed and highlighted in other briefings and studies. We should, however, emphasize that the word "nominal" implies that there are no firm requirements for the Future Transport Rotorcraft (FTR).

Figure 1 depicts the FTR as either a traditional helicopter or a tilt-rotor, capable of carrying an FCS in a cargo box with a volume equivalent to that of a C-130 transport aircraft. The vehicle would have sufficient range and payload to conduct a 500-kilometer radius (there and back) mission with vertical takeoffs and landings (VTOLs) at standard Army flight design conditions of 4,000-foot altitude and 95° F. It is assumed that the vehicle will be able to move the FCS around the battlefield and, hence, will need to repeatedly penetrate enemy air defenses.

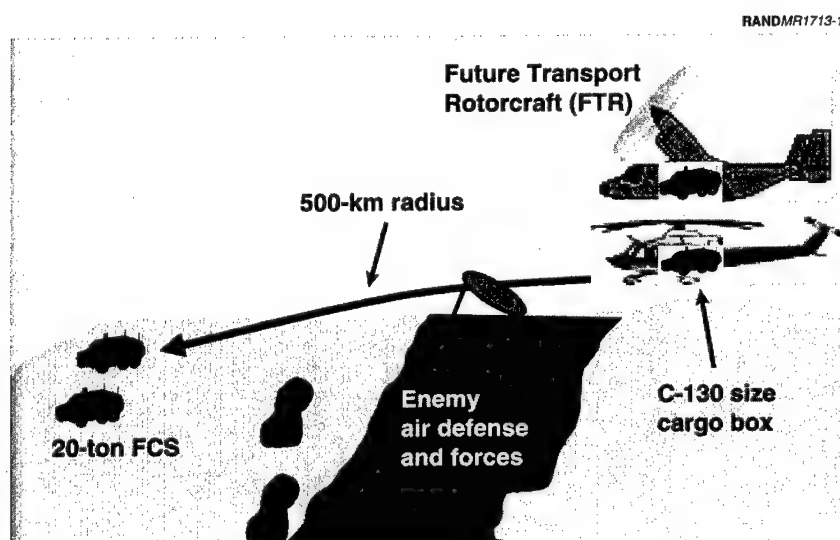


Figure 1—Vertical Envelopment and the Objective Force

We emphasize that the nominal design and operating parameters are not fixed. They do, however, serve as a starting point for analysis of the vertical envelopment mission in the context of the Objective Force. The concept also depends on compatibility between the FCS and FTR designs. Some refer to the two programs as being “joined at the hip,” though the FCS has a targeted deployment of 2010 while the often-discussed target date for the FTR is 2015. At this point, both dates appear optimistic, but it is not too early for there to be significant technical interchange between the two programs.

Those examining the future requirements of the Objective Force have identified an FTR capability as a dramatic force multiplier. Using wargames and high-resolution simulation modeling, Army “futurists” have demonstrated that if the rotorcraft can penetrate enemy defenses successfully, there are distinct benefits to deploying the FCS quickly and beyond enemy lines.¹ The deployed units can assume defensive positions in what was an offensive operation. These benefits are achieved with minimal collateral damage and are especially effective in complex-terrain settings where targets are difficult to find.

The Army’s rotorcraft community is equally enthusiastic about the FTR concept. The Army has sponsored a number of rotorcraft science and technology (S&T) programs for many years. Managers of these programs are optimistic that they can be used to develop an FTR concept that is affordable and feasible.

Although both Army military planners and technologists are attracted to the FTR, senior Army policymakers responsible for balancing a wider range of considerations have voiced skepticism. Some are concerned about the technical and financial feasibility of a rotorcraft capable of carrying 20 tons in an all-VTOL mode to a radius of 500 kilometers. They have also expressed interest in understanding the “knee in the curve,” that is, the point at which the technical challenges and uncertainties begin to grow and produce diminishing performance benefits. These considerations are important because

¹See Matsumura et al. (2000) and TRADOC Analysis Center (2000) for examples of modeling and wargames that validate the utility of the vertical envelopment concept under conditions where FTR survivability is not a factor. The former report also discusses survivability issues.

the nominal mission parameters are the basis for early discussion only. Ultimate mission needs might be altered, both for military reasons and for issues of cost and technical factors associated with either the rotorcraft or the FCS.

In addition to financial and technical questions, there are military issues that require further analysis. There is, of course, the need to better highlight the potential military benefits of vertical envelopment, but perhaps an even greater issue lies in the survivability of the large rotorcraft as it penetrates enemy lines. As noted above, the benefits of vertical envelopment occur only if the rotorcraft has freedom to move flexibly about the battlefield.

While it is not necessary to resolve all of these issues, it is important to provide enough definition to help structure the Army's Integrated Concept Team (ICT) effort. An ICT is one of the first steps in the military system acquisition process and is used to analyze needs and provide a more explicit definition of a system to fulfill those requirements.

More generally, the purpose of this report is to help the Army develop the FTR-FCS trade space. To date, the force developers have viewed the FTR as a "point design" concept, which either meets nominal vertical envelopment requirements or does not. Feasibility is tied to cost and technical risk, and there are many alternative design goals for an FTR. We note that the Army and rotor and fixed-wing aircraft developers have studied a range of aircraft for this application. This document endeavors to identify those complex factors so that the Army can make better choices with regard to the evolution of this technology.

ASSESSMENT OF EXISTING ROTORCRAFT TECHNOLOGY/COST

We begin our investigation of FTR feasibility by examining today's transport rotorcraft and the potential for extending their capabilities. We then consider the potential of advanced technologies and the risks and potential benefits associated with new science and technology concepts. An analysis of survivability issues follows, and we conclude by describing our recommendations for how the Army can continue to investigate the risks and benefits associated with this concept.

Figure 2 shows two pictures of the Soviet V-12 experimental rotorcraft that lifted 34 tons in 1969. This craft had two large rotors placed on wings supported by structural members, as seen in the left half of the figure. The V-12 was an experimental aircraft and flew only twice.¹

The V-12 illustrates an important point about the feasibility of the FTR. It is clearly possible to build a rotorcraft that is significantly larger than current vehicles. Specific to FTR, a helicopter based on current technology could be built and achieve the nominal requirements of 20-ton lift for a 500-kilometer radius. It is merely a matter of building large engines, cargo boxes, transmissions, and blades, all of which could perform at today's level of operating efficiency. The key questions involve the ultimate costs of such a vehicle, the cost risk, the risk associated with technologies aimed at improved efficiency and cost reduction, and survivability. Equally important are

¹See Alexander (1975) for a discussion of the V12.



Photographs courtesy of Ken Duffey.

Figure 2—The V-12 Lifted 34 Tons in 1969

reliability, operating and infrastructure costs,² and noise and vibration. Also critical is whether such a vehicle can be made acceptably survivable for the types of missions envisioned for its use.

CURRENT ROTORCRAFT CAPABILITIES

Figure 3 compares the nominal FTR requirements presented in Figure 1 with today's transport rotorcraft on a payload-radius chart. The payload-radius curves are developed for an all-VTOL mission (vertical takeoff with payload, vertical landing with payload). The curves have been developed for standard Army design conditions of 95°F and hover out of ground effect (HOGE) at 4,000 feet.

The curve shows the nominal FTR requirement at 20 tons and a 500-kilometer radius, and the ability to self-deploy. The figure also shows that today's large transport rotorcraft have problems meeting FTR requirements. The largest helicopter in the world is the Russian Mi-26. The Mi-26 carries a maximum payload of about 13 tons. The Army's CH-47F Chinook will be the next most capable (in terms of payload and radius) when it becomes fully operational. The U.S. military's heaviest lift vehicle today is the Marine Corps CH-53E Sea Stallion. The chart also shows the payload-radius capability of the Marine Corps V-22 tiltrotor. The tiltrotor can lift only 6 tons in these

²Current Army aviation infrastructure was not designed to support an FTR-type vehicle. The cost to upgrade facilities needs to be determined and should be the topic of future research once the FTR is better defined.

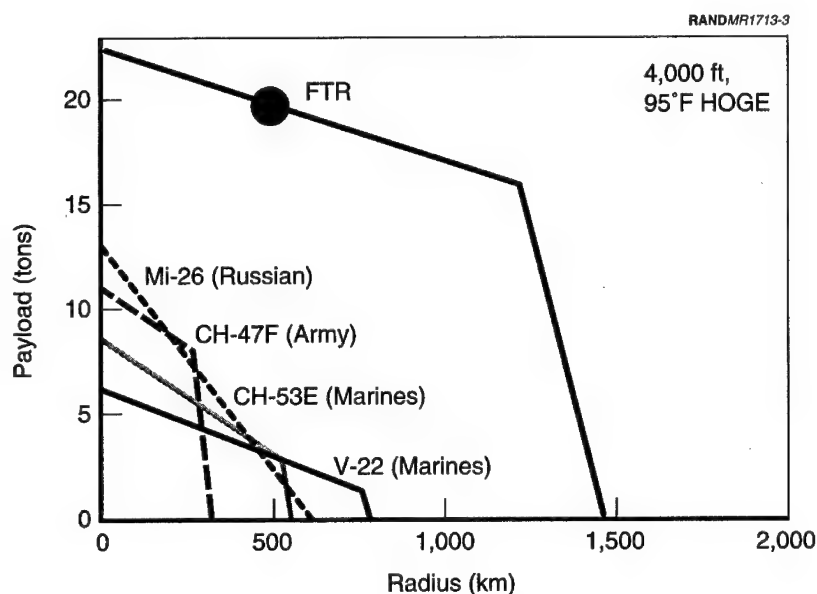


Figure 3—The FTR and Today's Large Rotorcraft

conditions, but the less severe slope of the radius-payload curve reflects better fuel efficiency in the turboprop mode. In contrast, the steep slope of the Mi-26 indicates poor fuel efficiency.

In addition to the radius-payload requirement, the FTR must have sufficient cargo volume to carry the FCS. Figure 4 illustrates the length and height of the cargo boxes of several relevant vehicles. Although the FCS is not yet designed, there is a preliminary assumption that it should fit within a C-130 cargo box. As shown in Figure 4, the Mi-26 already has a cargo box of equivalent size. The CH-53E has a similar but slightly larger box than the CH-47F, but they are roughly comparable and smaller than the Mi-26 or the C-130. The tradeoff between FCS performance and size has not been completed and may result in a vehicle that can fit in a CH-47F/53E cargo box.

The Mi-26 cargo box demonstrates that it is already possible to lift a cargo box of sufficient volume to carry the C-130 deployable FCS. However, the Mi-26 has neither the range nor the payload capability needed to transport the FCS, nor the fuel efficiency to meet the self-

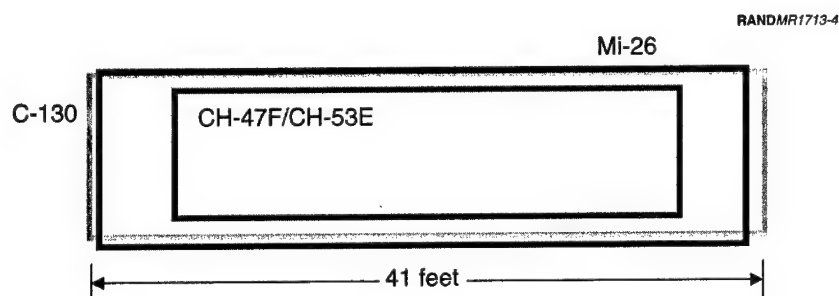


Figure 4—Mi-26 Cabin Size Already Adequate

deployment requirement. We do note that a Mi-26 upgrade program is being offered and may significantly improve these Mi-26 performance capabilities.

CH-53E UPGRADE

Figure 5 illustrates potential CH-53E upgrades with demonstrated subsystems.³ Replacement of the existing engines with larger, more fuel efficient, and lighter (per unit of power) engines, such as those used on the V-22, would dramatically increase the radius-payload capability of the Sea Stallion. However the curve would still lie well below the nominal performance requirement for the FTR.

Figure 5 also shows the impact of new blade technology on the radius-payload curve. This new blade is a combination of technology employed on smaller systems (the Black Hawk) and modest design advances proven in the laboratory. It would be an all-composite design with a new tip, and it would use today's airfoil technology.⁴

In one sense we can say that with the new engines and blades, we have reached the "knee" in the cost versus performance curve. After replacing the old engines with improved but existing engines and using new composite rotors, there are diminishing returns for the use

³The authors wish to thank Andy Keith and his colleagues at Sikorsky Aircraft for extensive explanations of CH-53 capabilities and for conducting numerous calculations and tradeoffs in support of our efforts.

⁴Communication from engineers at Sikorsky Aircraft.

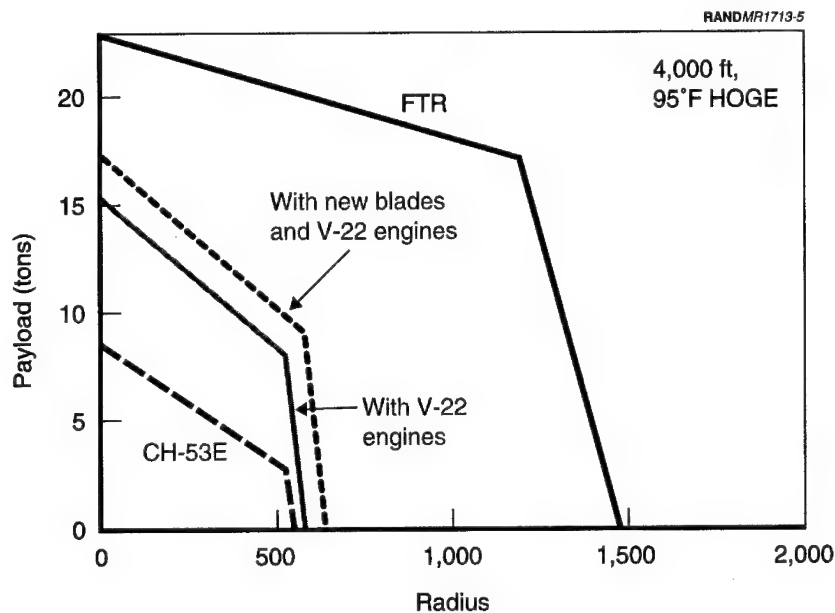


Figure 5—CH-53E Upgrade Options

of new technology to improve the performance of a CH-53E. A CH-47F would also need structural modifications to reap the benefits of new engines and rotors/blades. Even with these modifications, the CH-47F would not offer significant performance improvements over a similarly upgraded CH-53E.

We also note that the CH-53E cargo box displayed on Figure 5 could be enlarged to carry the largest FCS vehicle. This might cost as much as a ton of payload capability not reflected in the figure. Hence, the FTR design point is actually further from the CH-53E curves than indicated in the figure.

The performance versus platform cost curve will have a knee between modification of current platforms and the development of a new platform. By using the vendor's estimates for the possible improvements to a CH-53E we have identified the knee of this curve.

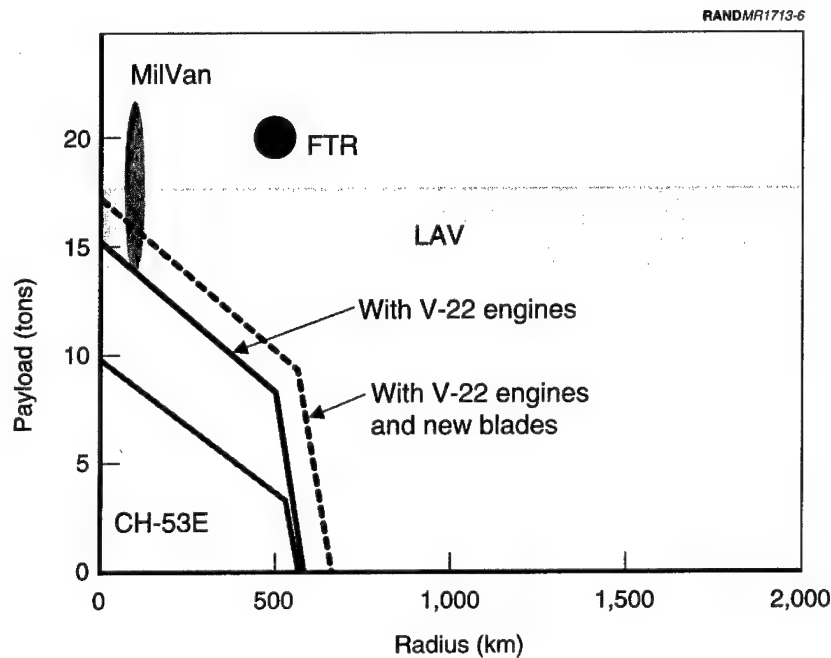


Figure 6—CH-53E Upgrades and Other Missions

Figure 6 displays the same radius-payload curves in Figure 5 and overlays two new missions that might be achieved by an upgraded CH-53E. These missions cannot be conducted with today's transport rotorcraft and may have relevance for the Objective Force.

MilVan containers are the military's units of packing for oceangoing freight. They can contain a maximum of 22.5 tons, though 90 percent of MilVan containers weigh 15 tons or less.⁵ Figure 6 shows that an upgraded CH-53E with V-22 engines could haul 90 percent of the MilVan containers over modest distances. It should also be noted that one of the key problems in the deployment of military units is the congestion point created when the containers are unloaded from ships. Upgraded CH-53Es could alleviate this problem by unloading

⁵Information provided by Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC).

these containers with an external sling. Since this unloading occurs at sea level, the payload capability is at least 10 percent higher than indicated in Figure 6.

Another mission involves movement of the Light Armored Vehicle (LAV). The Marine LAV I weighs around 14 tons, and the Army's Stryker interim force combat vehicle (based on the LAV III) will weigh around 18 tons. While the latter is somewhat beyond the radius-payload capability displayed here, we should remember that the curve in Figure 6 is for an all-VTOL flight at a 4,000-foot HOGE and at 95°F, with two landings and takeoffs. Under less stringent conditions, it is possible to consider the use of large transport rotorcraft with today's subsystems to deploy the Stryker in a limited vertical envelopment scenario.

CHAPTER SUMMARY

Today's helicopters fall far short of the goals of a 20-ton payload with a 500-kilometer radius. Upgrading existing rotorcraft with modern large engines might allow for fulfillment of the mission if the FCS is only 12–15 tons and a shorter radius is required. We do, however, caution that the FCS might need to be sling-loaded, as even a 12-ton FCS might not fit into the CH-53E cargo box. Of course, one other option is to seek modernization of the Mi-26. We should also mention that modernization of the CH-53E or Mi-26 might also allow fulfillment of other missions such as movement of MilVan containers and possibly movement of the Marine LAVs and Army Strykers.

The RDT&E cost to develop new aircraft has varied from approximately \$9 billion for the C-17 to \$11 billion each for the RAH-66 and V-22. Complex aircraft such as the F-22 and F-35 are expected to have RDT&E costs in excess of \$20 billion. Comparing these costs to the \$100 million to modernize the C-130H to the C-130J and the few hundred million dollars needed to modernize a CH-53E or Mi-26, we identify our first "knee in the curve." The development cost versus FTR performance curve clearly has a knee between modernization and new start.

ADVANCED TECHNOLOGY ROTORCRAFT

Chapter Two highlighted the potential of today's rotorcraft and the limitations of using these vehicles, even when upgraded to include the most modern, proven subsystems. However, the figures also indicated that such upgrades could perform new and useful missions relevant to the Objective Force. These missions are less demanding than the nominal FTR vertical envelopment mission.

In this chapter we consider the role of advanced technologies in achieving the nominal FTR requirements. As noted previously, it has been possible for many years to build a rotorcraft that has the lift and radius potential of the nominal FTR. The key issues are cost, reliability, and survivability.

COST/WEIGHT

Figure 7 shows weight and cost estimates from the Army's Aviation and Missile Research, Development, and Engineering Center (AMRDEC) for vehicles meeting nominal FTR requirements as a function of the level of technology employed.¹

The bar on the left indicates weight and cost estimates using today's subsystems. Since there are no actual turboshaft engines, drive trains, and blades of sufficient size, the estimates are based on scaled versions of existing systems, under the assumption that there would

¹AMRDEC senior analyst Mike Scully provided the data. The results are similar to those developed by Sikorsky Aircraft.

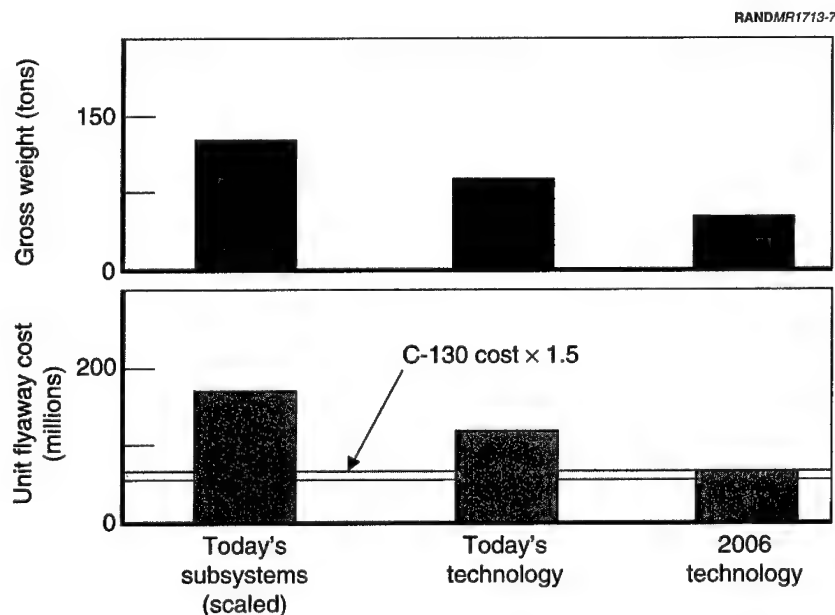


Figure 7—Cost/Weight Estimates for the “Nominal” FTR (AMRDEC)

be no technical improvement in their performance. For example, the engine would maintain the same power-to-weight ratio and specific fuel consumption as today's modern engines. The middle bar shows the expected reductions in cost and weight if new subsystems were designed based on today's component technology and technology demonstrated at the laboratory breadboard level. Whether such components could be efficiently converted to subsystems is an open question. Finally the bar on the far right shows the reductions in cost and weight achievable if AMRDEC's 2006 science and technology (S&T) research goals are achieved. The lower graph shows that achievement of those goals would bring the costs of the rotorcraft in line with the historical 50 percent distinction between rotorcraft and fixed-wing costs for similarly sized payload capabilities.

Figure 7 shows the necessity of reducing significantly the expected costs of the FTR (with provisions for Naval applications). AMRDEC estimates the cost of the FTR to be approximately \$250 million/copy with today's available subsystems technology. Assuming a fleet of

500 FTRs used on one Army wargame, and the need to buy approximately 1.5 vehicles for each deployed in the field, the cost of the full FTR fleet would be approximately \$187 billion with today's subsystems. FTR fleet cost would be \$126 billion (\$168 million/copy) using today's technology, and \$75 billion (\$100 million/copy) using technology we hope to demonstrate in the next five years. Even the latter figure would strain Army budgets and would be a realistic option only if the system were survivable and viewed to offer a decisive advantage in a wide range of scenarios.

S&T GOALS

Army S&T goals for 2006 are summarized in Figure 8.² It is important to note that several of the goals will lower FTR costs, such as reduced manufacturing costs, and higher power-to-weight ratios for the transmission and engines. Other goals, such as noise and thermal signature suppression, will increase costs and, to a minor extent, weight. The relationship between weight and cost is dependent on other design specifications. One good example is the S&T goal of developing lighter transmission systems that are 15 decibels quieter than current systems. Lighter transmissions tend to use more expensive materials. They also tend to be noisier, requiring extra noise-reduction materials. More precise manufacturing of the transmission parts can help reduce transmission noise, but this increases the cost of the transmission. The use of new technology such as noise-cancellation helmets/headsets could be a relatively inexpensive part of an overall solution to reduce transmission noise to acceptable levels for the FTR crew. Such a solution, however, will impose some communication constraints on the crew and passengers and must be balanced with mission needs. The relationship between weight and cost for the transmission will be determined by the combination of extra materials, precision machining, and noise-reduction technology used in the specific design and will be platform specific.

²After this report was written, S&T emphasis shifted from the FTR to UAVs. Most of the UAV S&T goals are consistent with the S&T goals in Figure 8; however, certain goals will be delayed beyond 2006. Given the change in Army leadership, S&T goals will probably change yet again.

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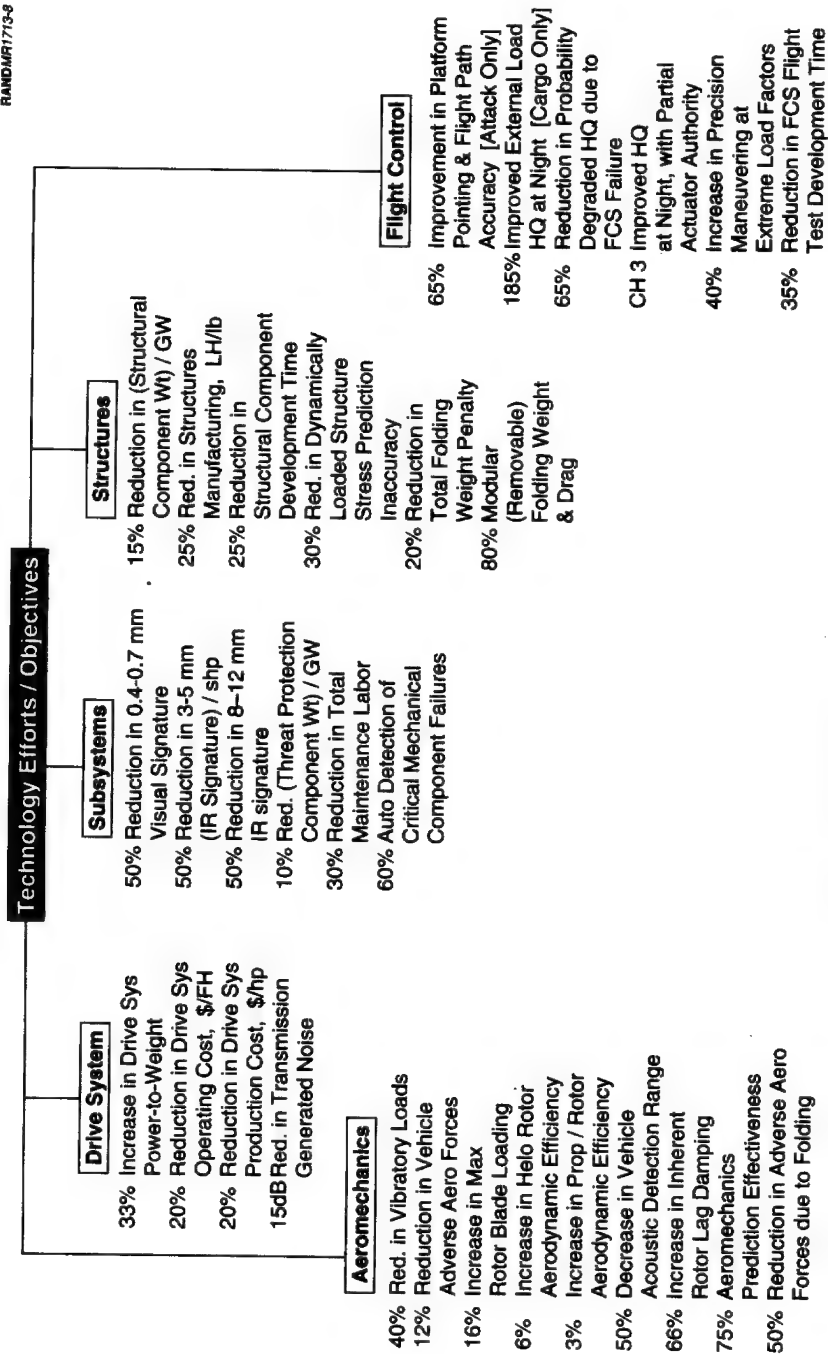


Figure 8—Phase II Rotorcraft S&T Goals

Our cost estimates are based on a linear relationship between weight and cost. The weight-cost relationship is partially causal. A larger transport rotorcraft requires bigger engines, more rugged transmissions, more materials, and larger subsystems. However, it is important to realize that the weight-cost relationship also has a historical origin, in that a plot of helicopter weight and cost over the years will yield a somewhat linear trend. It is also improved by considering other parameters such as total power, technology, and complexity as inputs to its cost model in the historical relationship.³ As discussed above, the specific design performance requirements will be significant cost drivers.

Given the lack of actual designs, weight is a useful surrogate for cost for policy analysis. However, the information in Figures 7 and 8 should lead Army policymakers to ask two critical questions: First, how likely are we to achieve the science and technology breakthroughs in the rotorcraft goals? Second, if those breakthroughs are achieved, will the lower weight result in lower costs?

FTR CONCEPTS

Figure 9 provides schematics of four alternative designs to fulfill the nominal FTR mission. The blade dimensions are based on calculations that assume we achieve the weight reductions and increased lift specified in the Army's 2006 S&T goals. Should those weight reductions not be achieved or the innovative blades not provide the increased lift, then they would need to be larger.

Figure 9 shows the dimensions for traditional helicopters, a dual tiltrotor, and the so-called quad tiltrotor. The tiltrotors have the advantage of flying with greater fuel efficiency but are technologically more complicated than traditional helicopters. This has been illustrated by the continuing problems confronting the Marine Corps V-22 conventional tiltrotor. The quad reduces the structural and aeroelastic problems posed by placing very large engines on the wing tips, but it creates uncertainties about the aerodynamic interaction among the four rotors.

³See Harris and Scully (1998) for a discussion of rotorcraft cost estimation.

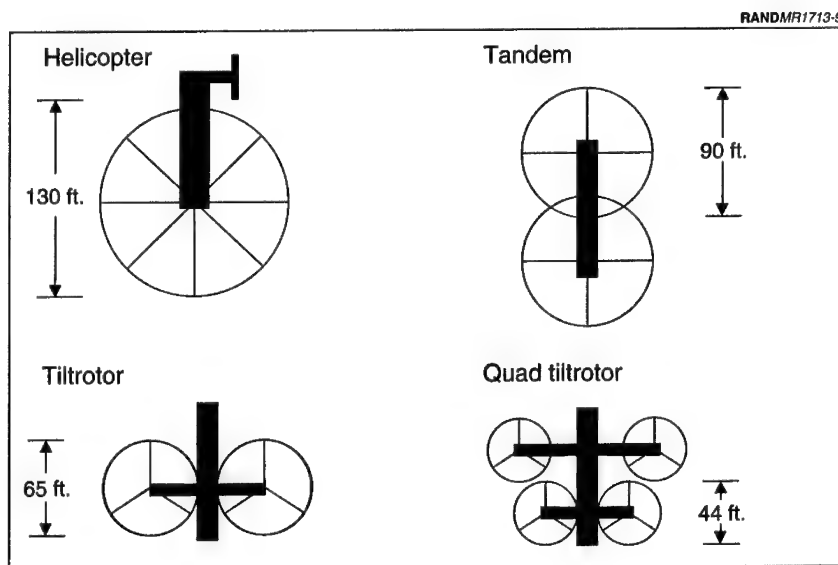


Figure 9—2006 Technology Concepts Limited to Preliminary Sizing Calculations

The estimate of \$100 million for each FTR is based on preliminary sizing calculations rather than an actual design drawing with detailed specifications. We note that historically, costs have risen for almost all weapon systems as they have proceeded from this level of analysis to more detailed design.

TECHNOLOGY VERSUS COST

Figure 10 provides an additional reason to be cautious about the relationship between technological progress and cost reductions that underlies Figure 7.

If developments like those depicted in Figure 7 occur simultaneously in areas such as transmission systems, blade design, cargo box manufacturing, cargo-handling systems, and cockpit design, then it may be possible to develop the nominal FTR at weights illustrated in Figure 7. A preliminary assumption has been that decreased weight results in decreased cost.

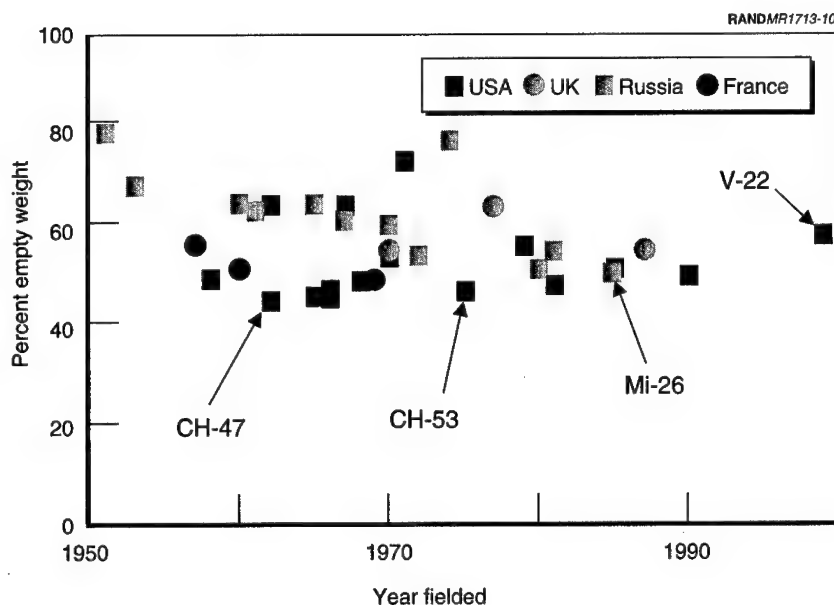
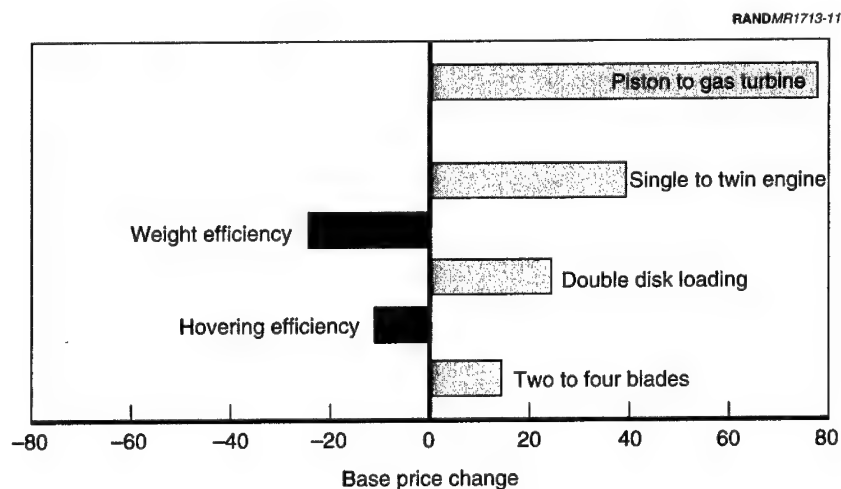


Figure 10—Performance Improvements Have Kept Empty Weight Percentage from Declining

If S&T developments are successful, there is also the possibility that this technical progress will not result in decreased overall vehicle weight. Figure 10 displays empty weights for military helicopters (percent empty weight is equal to the empty vehicle weight divided by the gross weight; gross weight is empty weight plus fuel plus payload) and indicates that technical progress has not resulted in any obvious pattern of reduction in the empty weight fraction.

The pattern displayed in Figure 10 is typical of the evolution of many weapon systems. Technical progress is used to increase system performance rather than to lower costs. If the FTR is to achieve lower weight (and cost), then it will be necessary to impose a discipline on the acquisition process that minimizes performance enhancements and concentrates on achieving the minimum requirements for the vehicle.

In addition to concerns about translating technical improvements into weight (cost) reductions, Figure 11 shows that many past rotorcraft product improvements have not resulted in price reductions. The largest increase came with conversion to the gas turbine engine, which supplies more power at lower weights but has steep manufacturing costs. Twin engines increased price and were largely driven by safety concerns. The cost increase arising from the increase in disk loading is due largely to the need for increased power to compensate for the smaller rotor size.⁴ More sophisticated cost models show that power can be at least as important a correlate of cost as weight. The increase in the number of blades from two to four reduced vibration, at the expense of system complexity, which may have been responsible for cost increases. Figure 11 shows that improvements in hovering efficiency and weight efficiency have been the only two developments that led to reduced costs.



SOURCE: Harris and Scully (1998).

Figure 11—Historically, Product Maturation Has Not Lowered Price

⁴Disk loading is the weight of the aircraft divided by the circular area swept by the blade.

Figures 9–11 highlight uncertainties about whether cost reductions would be realized, assuming Army S&T goals were achieved. Figures 12 and 13 suggest that there is substantial uncertainty about the achievement of those goals.

The concepts in Figure 8 are viable only if the S&T goals established by the Army can be achieved. Completing these goals by 2006 would allow FTR deployment in 2016, if we assume an accelerated schedule for FTR development. Of course it is difficult, if not impossible, to precisely determine what can be achieved in an S&T program, though Figure 12 places the Army goals in the context of the historical development of engines. The figure shows turboshaft engine power-to-weight ratios for deployed rotorcraft. As indicated, there has been a slow evolution from the 1960s to the employment of the Allison T406 engine in the V-22. This is the same engine that could be used to modernize the CH-53E (as indicated in Figure 5).

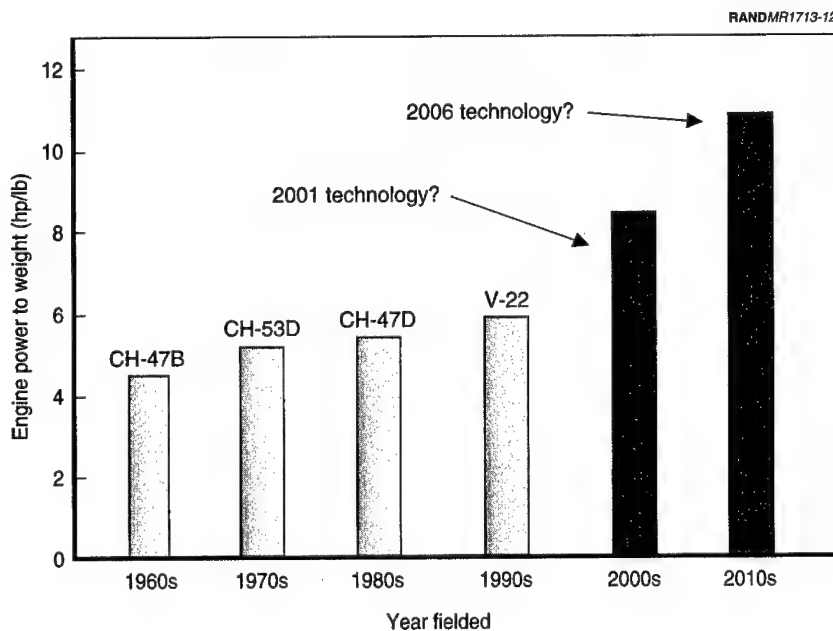


Figure 12—Lower Weight Concepts Depend on Accelerating Technology

Figure 12 also shows the engine technology goals embodied in the “today’s technology” and “2006 technology” bar graphs in Figure 7. By today’s technology, we mean technology that has been demonstrated in a laboratory environment. In this case, the level of today’s technology has been validated by the Army-managed Joint Turbine Advanced Gas Generator (JTAGG) program. In this program, experimental engine cores have been run at test conditions and demonstrated the power-to-weight ratios shown above. The Army’s JTAGG program has maintained a steady level of progress, and if current trends continue, we would expect a continued improvement in parameters like the power-to-weight ratio for the experimental engine cores.

Figure 12 indicates that today’s technology would result in an engine in the 2000s, while “2006 technology” would produce a new engine in the 2010s. The gap between today’s technology and deployment is due to the numerous developments that must occur between the demonstration of an engine core in a laboratory environment and the fielding of an operational system. The key to increasing engine power-to-weight is to operate the engine at higher temperatures. In comparison to field conditions, doing this in a laboratory is a relatively straightforward task. There is a potential problem of turbine erosion with the dust and particles encountered in operational conditions at high engine temperatures. The dust and particles may cause engine damage. In an operational FTR unit, an engine should be built to last for thousands of hours, while in the laboratory it is only necessary to perform for tens or hundreds of hours.⁵

There are at least two major development phases required before an engine core using today’s technology in a laboratory setting could be transformed into an engine in an operational rotorcraft. First, the complete engine would have to be developed and tested in the laboratory environment. The next phase would be testing in operational environments for extensive periods.

There has been slow improvement over the last several decades, but achieving the lower weights depicted in Figure 12 will require progress at a far greater pace.

⁵It is possible but costly to replace engines on an as-needed basis.

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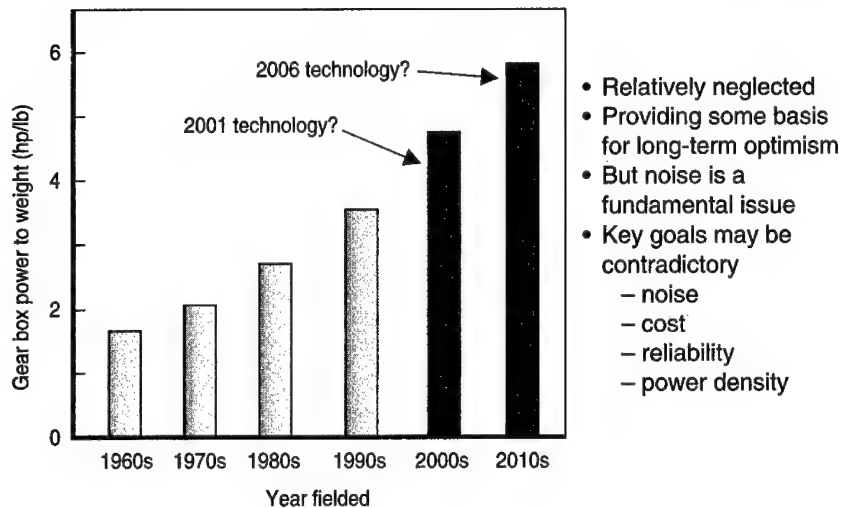


Figure 13—Transmissions

The Army's 2006 S&T goals involve technologies related to subsystems. Figure 13 highlights issues associated with the goal of improving transmission systems. The 2006 goals are to develop technology for a transmission that is lighter for a given power load, less noisy, more reliable, and less costly. Relative to the CH-47D Chinook, the Army's heavy lift helicopter, Army goals are for a 35 percent increase in the power-to-weight ratio, a 15-decibel decrease in noise, and a 25 percent decrease in production and maintenance costs.

The left half of Figure 13 illustrates the historical trend in gearbox power-to-weight ratio. The right half indicates the progress that will have to be made in the next two decades. As indicated above, this will require a steady continuation of the progress made over the last several decades. In contrast to engine development, drive systems have been a relatively neglected area for rotorcraft S&T expenditures. There are promising new technologies, such as split torque and face gearing, that could provide the needed progress. With split torque there are two or more high-speed gears that transmit the torque to the same low-speed bull gear. This is already done on the Co-

manche. Perhaps the most critical outstanding issue is the ability to manufacture the gears to the required hardness.

We conducted interviews with transmission experts⁶ around the country and concluded that there are grounds for cautious optimism with regard to achieving significant benefits in each of the four areas. For example, a new ability to model operating stresses may offer the prospect of improved reliability. Split torque may reduce material requirements and possibly lower costs.

Our interviews indicated that noise⁷ has been a neglected area of transmission S&T that needs more research funding. One significant challenge associated with future drives is to achieve both noise and weight reduction simultaneously. The most direct approach to reducing noise is to provide additional material buffers. However, this is in direct contradiction to the goal of making the system lighter and, by inference, less costly. Most experts referred to the need for fundamental research before arriving at attractive strategies for dealing with noise while also lowering costs.

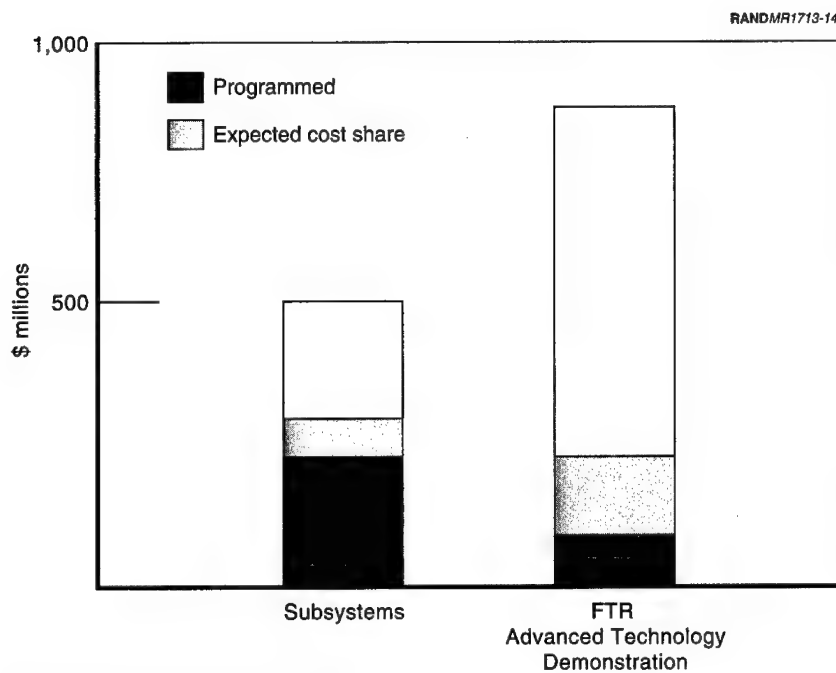
In summary, there is reason for cautious optimism that a dedicated R&D effort might improve the performance of existing transmission systems. However, the hope of achieving all the 2006 goals for all subsystems does not appear to be realistic. It would require technological progress well beyond historical rates for many mature technologies.

We should keep in mind that the demanding nominal FTR requirements are not firm and will be subject to significant amendment. Less stringent requirements could ease the demand on Army S&T to achieve dramatic breakthroughs.

Figure 14 shows the financial needs specified by the Army's S&T community to achieve the 2006 goals listed in Figure 8. Approximately \$500 million is needed to conduct work on subsystems such as the engine, transmission, blades, cargo-handling system, cockpit,

⁶Interviews with transmission engineers and researchers from NASA's John H. Glenn Research Center, Lewis Field, Ohio, Boeing, Sikorsky Aircraft, Bell-Textron, and Ohio State were conducted on a nonattribution basis during the course of this study.

⁷Ergonomics and FTR acoustic signature came up in the interviews as critical issues associated with excessive transmission noise.



Budget data supplied by AMRDEC.

Figure 14—S&T Needs 2003–2007

etc. Of this, approximately half is already programmed, and Army personnel expect industry to share a small part of the cost. A full-scale ground Advanced Technology Demonstration (ATD) would cost approximately \$850 million, and there is little programmed funding for this activity.

These costs include provisions for competitive demonstrations. A decision to move forward in a noncompetitive mode would lower the estimates. There are enough programmed funds for a single demonstration of every subsystem except the engine. Those funds could be drawn from the funds currently programmed for the ATD. Thus, every subsystem could be demonstrated using funds already programmed.

To better understand the knee in the technology risk curves, we use NASA's technology readiness levels (TRLs) to evaluate the four basic design concepts. Listed in Figure 15, the TRLs use well-defined qualitative observables to generate a numerical risk assessment. In general, TRLs of 6 or 7 should be obtained before committing to a new start.

Figure 15 summarizes our assessment of the TRLs of the four potential FTR designs. It is possible to build a helicopter based on demonstrated subsystems that are larger than those used on today's rotorcraft but that perform at similar levels. However, the weight

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NASA TRLs

Basic Technology Research

Level 1: Basic principles observed and reported

Research to Prove Feasibility

Level 2: Technology concept and/or application formulated

Level 3: Analytical and experimental critical function and/or characteristic proof of concept

Technology Development

Level 4: Component and/or breadboard validation in laboratory environment

Technology Demonstration

Level 5: Component and/or breadboard validation in relevant environment

Level 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space)

System/Subsystem Development

Level 7: System prototype demonstration in a space environment

System Test, Launch, and Operations

Level 8: Actual system completed and "flight qualified" through test and demonstration (ground or space)

Level 9: Actual system "flight proven" through successful mission operations

RAND assessment of FTR TRLs

Helicopter (single and dual rotor) 5, Dual tiltrotor 3–4, Quad tiltrotor 3

Figure 15—Analysis Using NASA's TRLs Indicate Quad Tiltrotor Has the Highest Technical Risk of the Four Proposed FTR Design Concepts

and presumed cost of such a system implies that this is not a serious option for an FTR with a 500-kilometer mission radius.⁸

Achieving the S&T 2006 goals will require acceleration in the pace of technology beyond what has been achieved historically. There is also a question about whether technical progress will actually lower costs. This concern arises because: (1) the cost-weight relationship is primarily historical rather than causal, (2) Army S&T goals are (partially) driven by weight reduction and the implicit assumption that this will produce cost reduction, and (3) history has shown that it is difficult to achieve cost reduction in rotorcraft.

The tiltrotor designs have more technical risk than the helicopter designs. There is considerable risk in proposing a design based on a TRL of 3. The knee in the technology risk curve is between 3 and 5 (helicopters and tiltrotor craft). A quad tiltrotor may have significant operational value, but in our estimation the technical risk is significant, and a tiltrotor FTR may not be ready for combat in 2020.

We note that the Army's S&T program has as a 2006 goal the demonstration at TRL 6 of several of the major subsystems. TRLs should be reevaluated as significant results occur and are evaluated. Our assessment was based on technology demonstrated as of July 2001.

⁸The mission radius is the primary cost/risk driver for the FTR; a 250-kilometer mission radius could be a serious option.

SURVIVABILITY CONCERNS

This chapter presents our analysis of several critical survivability issues for the FTR. To achieve the benefits of vertical envelopment, the FTRs have to fly missions in the enemy's second and third echelons with significant flexibility and without the need to delay flights because of survivability concerns. The survivability of the FTR under different levels of enemy air defenses is a critical issue for the vertical envelopment concept. The enemy's ability to change his tactics, technology, and troops to minimize the impact of vertical envelopment must also be considered. To understand what survivability issues may be when the FTR is fielded, we conducted an assessment of current and projected future threats and countermeasures. We also investigated trends in the counter and countercountermeasure competition to better illuminate the challenges for FTR designers.

FTR SURVIVABILITY AGAINST CURRENT RUSSIAN AIR DEFENSE SYSTEMS

Figure 16 illustrates a lay-down of two-thirds of the air defense assets (ADA) that would be available today to a Russian army in an offensive operation. We assume one-third of the assets have been used or lost during an initial attack in which the Russian-equipped forces crossed the border and secured a 250×250 -kilometer portion of territory (grid squares are 50×50 kilometers). We assume vertical envelopment implies the air insertion of the brigade combat team in the landing area shown in the figure. As a point of comparison, the density of anti-aircraft artillery (AAA) in Kosovo was ten times what is shown in Figure 16. Admittedly, the overall air defense in Kosovo was less sophisticated than the threat depicted in the figure.

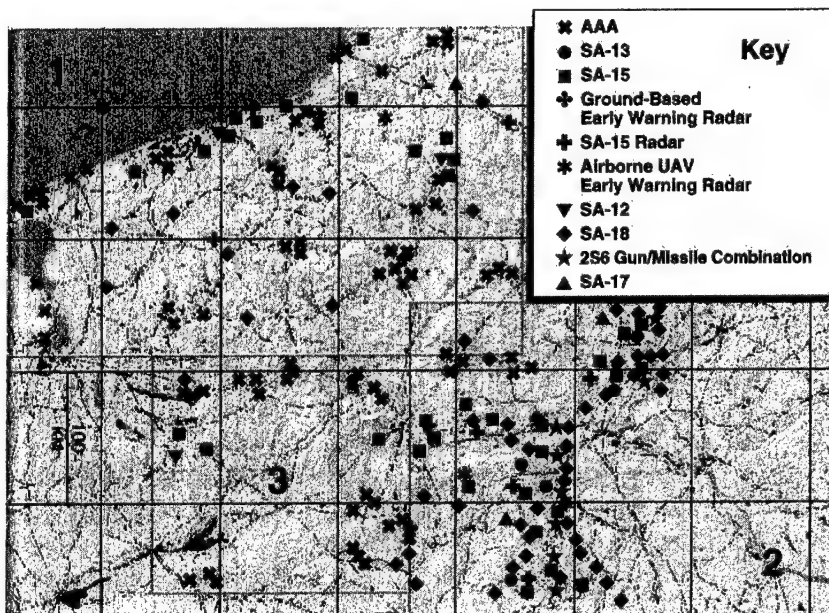


Figure 16—Air Defense Laydown Based on Current Russian Army Capabilities

Air Defense assets shown in Figure 16 include: the SA-12, a long-range (150-kilometer) radar-guided missile system comparable to Patriot; the SA-17, a medium-range (50-kilometer) radar-guided missile capable of engaging high-altitude targets (25 kilometers); the SA-15, a short-range (12-kilometer) radar-guided missile system mounted on an APC; the 2S6, which is similar to the SA-15 with an additional 30mm radar-guided AAA. The SA-18 is a third-generation, man-portable, IR seeker surface-to-air missile. Typically deployed in groups of two men, each with a launcher and two or more missiles (often referred to as a man portable air defense system, or MAN-PADS), the missile has a range of over 5 kilometers. The SA-13 is a second-generation IR SAM typically mounted on a tracked vehicle with a target-acquisition radar. The SA-13 missile is effective out to 5 kilometers. AAA for this application can be either optically or radar-guided and is effective against targets at ranges of 3 to 4 kilometers. Most of the missiles and AAA can hit aircraft flying as low as 10 meters above ground. Performance parameters are from *Jane's Air*

Defence 1999–2000 and represent open literature estimates of ADA performance.

The laydown of ADA assets in Figure 16 allow us to test two levels of defense. Lower-quality units (truck-mounted infantry, for example) are along the coast and guard against vertical penetration from the water. In our simulations, we had Navy and Army helicopter pilots fly from point 1 to point 3 with various levels of situational awareness (SA), IRCM and RFCM, and suppression of enemy air defenses (SEAD). These units have considerably fewer air defense systems than the units along the forward line of troops (FLOT), which is to the east of the landing area (pilots flew the FTRs from point 2 to point 3). SA-15 coverage, for example, has several small gaps along the coast but none along the FLOT. There are no 2S6 or SA-13s deployed along the coast. In addition, there are far fewer SA-18 MANPADS along the coast than at the FLOT.

Figure 17 shows the results of RJARS¹ (RAND's Jamming Aircraft and Radar Simulation) runs aimed at modeling the coastal penetration of 42 FTRs flying in tactical trail formation (groups of 3 with 100-meter separation) to the landing area going through the defenses shown in Figure 16.

The figures show that whether the FTR has a large set of signatures (the radar, optical, and IR signatures are assumed to be twice as large as those of a current rotary-wing transport aircraft) or uses current helicopter stealth technology any attempt to fly the vehicles without SEAD or SA results in 100 percent loss of the aircraft. This occurs for penetration routes from cross-FLOT and from the ocean. Attrition levels drop to a still unacceptably high level if we assume suppression of all air defense radar sensors (high SEAD) and/or high SA (meaning the pilot has knowledge of the location of all RF emitters, radiating or not) similar to Operation Desert Storm. Even with the less demanding ocean flight penetration routes and usage of low-signature rotorcraft, the 15 percent sortie attrition rate is, for most missions, far from acceptable. We also note that because RJARS does not model the acoustic signature, the results would be even worse if acoustic anti-helicopter mines were deployed. In addition, passive

¹The RJARS simulation model is described in Sollfrey (1991). RJARS has been updated as new threats were considered and model capabilities enhanced.

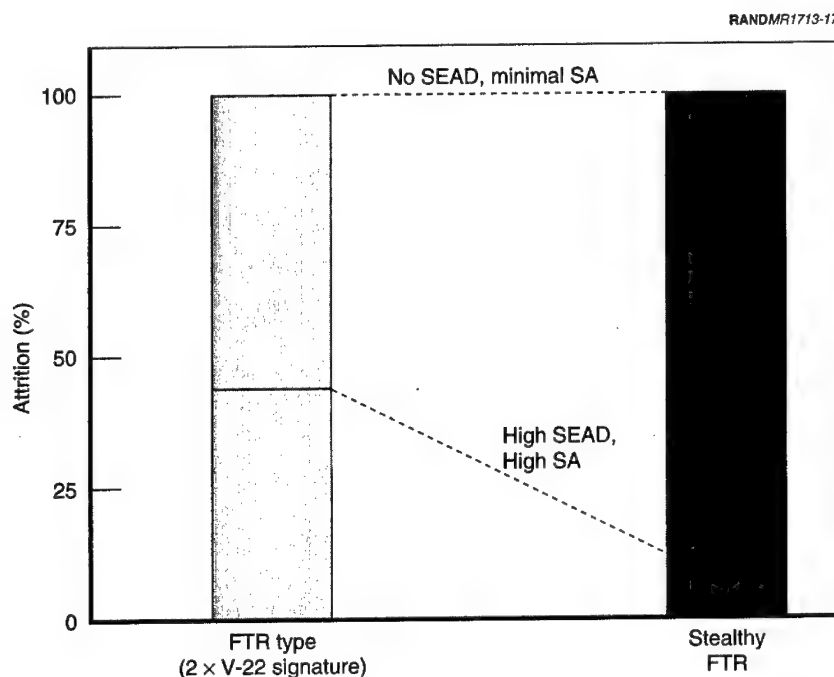


Figure 17—RJARS Results for Low-Altitude Routes from the Coast

acoustic detection of the rotorcraft acquisition would enable AAA, RPGs, and IR SAMs to be cued to the rotorcraft without the help of search radars.

The results in Figure 17 indicate that in a high-threat environment, the FTR, even with dramatic success in research on signature suppression, will not be able to fly freely about the battlefield. There is a requirement for extensive SEAD and a set of operational protocols to improve survivability, but that will inevitably limit flexibility. For example, it may be necessary to fly around defenses or to fly only on penetration routes where the ground has been secured. However, SEAD is unlikely to destroy every machine gun, RPG, and IR SAM. The latter are highly mobile, small, and easy to hide in complex terrain. The current U.S. Air Force strategy of flying above these low-altitude air defense threats is clearly validated by our modeling effort. With tiltrotors, the Army could fly above these threats but will still

need to land, unlike the Air Force, in enemy-controlled areas. The maximum threat the aircraft can land in becomes the key issue if the fly-high tactic is used.

For the next two figures we reduce the level of defense to identify the minimum level of ADA the enemy needs to cause significant operational problems for the vertical envelopment concept. Other SEAD approaches using extensive onboard countermeasures are possible and will be discussed later in this chapter.

The results in Figure 17 led us to ask a different question: "What is the maximum level of defense that the FTR could fly through/land in without requiring significant operational support or modification?" Figure 18 shows a laydown typical of a Russian enemy infantry company given a mission to defend a key position against ground and air attacks. The company has six rocket-propelled grenades (RPGs), nine hand-held machine guns (HMG), and three tanks with a 125mm gun, each of which carries a single SA-18 hand-held IR SAM system (MANPADS). All the APCs have 30mm chain guns, which are modeled as anti-aircraft artillery. The vehicles all have thermal and opti-

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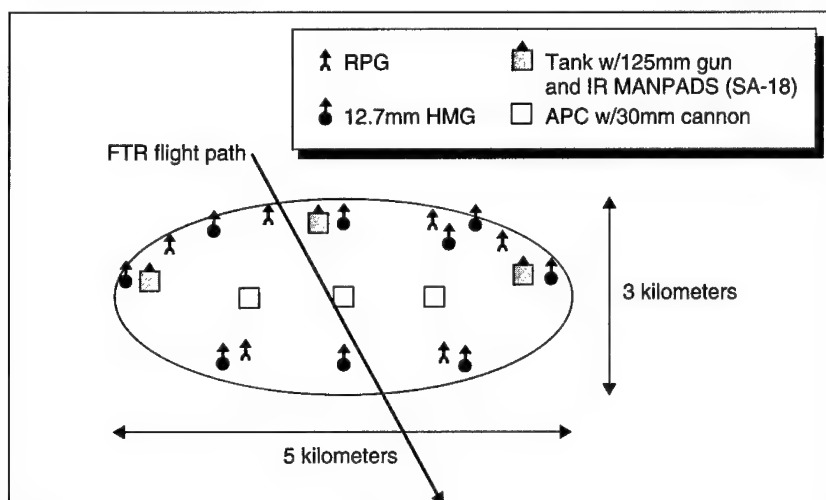


Figure 18—"Typical" Enemy Infantry Company

cal sights. The company is distributed over a 3×5 -kilometer area. Each weapon system is modeled as an independent ADA and given orders to fire at any aircraft within its lethality range.

Figure 19 shows the results of flying a group of 42 FTRs over the infantry company (path shown in Figure 18.) The results show unacceptably high attrition rates for the large-signature FTR, even in the case where the tanks and their associated MANPADS are removed. It is only in the case where signature reduction occurs, along with elimination of the MANPADS, that attrition rates reach the level where we can begin to contemplate use of the FTR without significant operational limitations or conditions. Aggressive use of IR countermeasures can help negate the IR SAM threat, but even a factor-of-five improvement over current IRCM still results in high sortie attrition rates. We also note that AAA effectiveness is dependent on vehicle size. If we model an FTR with current helicopter stealth technology and the physical size of two V-22s, its sortie attrition rate, for the no IR SAMs case, is the same as the base case.

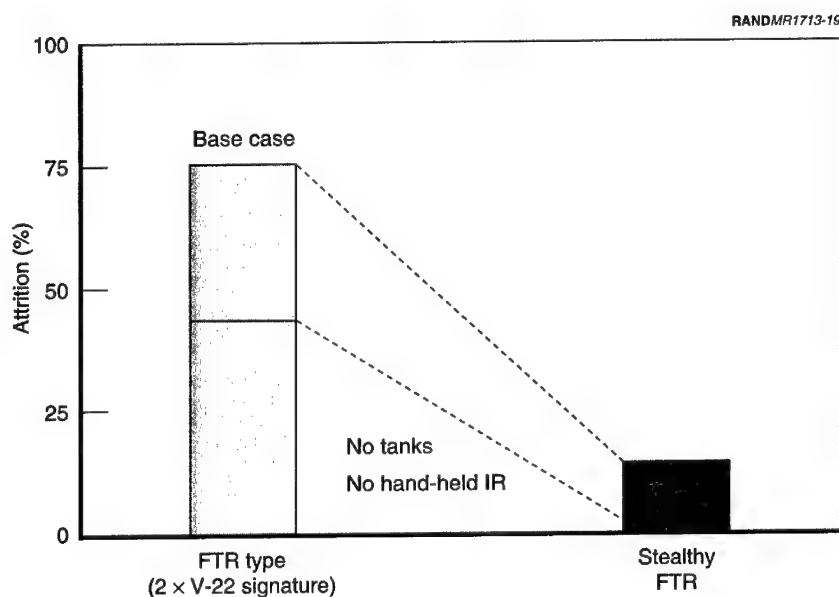


Figure 19—FTR May Be Vulnerable to Very Thin Defenses

COUNTERMEASURES

Concerns about FTR survivability have been raised in several forums, and it is not uncommon for these concerns to be answered by expectations that technical advances in countermeasures may offset the threats. Figure 20, however, shows that an assumption of countermeasures effectively counteracting the MANPADS threat would require a reversal of the historical trend in this technology. Historically, the offensive threat has consistently stayed ahead of the defensive countermeasures.

IR SAMs were introduced in the late 1960s in Vietnam. The Soviet SA-7 and the U.S. Redeye were the first-generation IR SAMs. They used a low-performance uncooled IR detector and a spinning reticle to track and provide inputs to the missile guidance system. The target signal was an amplitude-modulated signal that was minimized when the target was centered on the spinning reticle. As the target maneuvered, the detector's output signal increased with the amplitude proportional to the angle (off center) of the target relative to the missile. Flares could counter this type of seeker by generating a

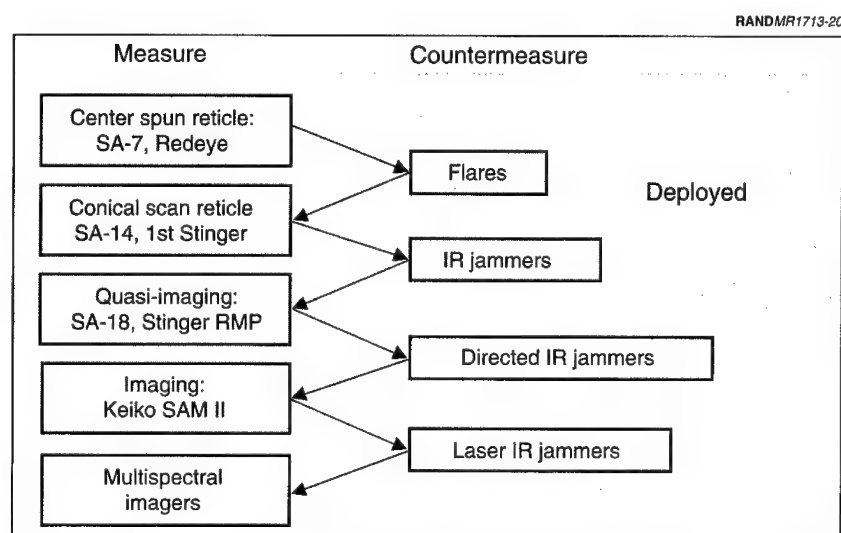


Figure 20—Hand-Held IR: Offense Leads Game

signal brighter than the aircraft, causing the seeker to track the brighter object and ignore the actual aircraft signal.

The basic Stinger and SA-14s and 16s were developed to counter flares. Here the reticle is spun as well as a mirror in the missile receiver optics. Called FM conical scan, this approach gives an FM signal that is tracked. Since the signal is always present (not minimized like the spin reticle), the missile is flare-resistant. That is, it will not track a flare, though it may center on a point between the aircraft and the flare. The seeker's narrow field of view causes it to center on either the aircraft or the flare as the missile approaches the aircraft. Two countermeasures to the FM conical scan missile were developed. The first is to pop a series of flares so that the seeker is confused by the time average center of the flares and aircraft (limited by the need for large numbers of flares). The second countermeasure is an IR jammer, consisting of a bright xenon lamp modulated at the seeker's tracking frequency. This disrupts the phase-locked electronics in the missile's receiver. This may be successful if the defense knows the modulation format of each IR SAM deployed in theater. It also requires the jammer signal to be roughly five times greater than the aircraft's signal to "disrupt phase lock," a problem with today's transports' high IR signature.

In any case, third-generation missiles were already deployed when IR jammers were deployed. Quasi-imaging sensors use a scan mirror and a detector array, or one detector and two scanning mirrors, to trace out a rosette pattern to generate the image. The rosette pattern used in later versions of Stinger does not revisit the exact same "pixel" each cycle, so jammers need a much higher jammer-to-target-signal ratio to guarantee that enough jamming signal gets through. The scanning system can, in theory, home in on the jamming source. With enough jamming signal you can saturate a block of angular space around the aircraft and hope the missile circular error probable (CEP) is enlarged accordingly. Directed IR countermeasures (DIRCM) can give the higher jammer-to-signal ratio needed, but this technology is still in engineering development. The programs have also been subject to funding cutbacks and cost overruns. The missiles have been in production since the late 1980s.

DIRCM and flares may not be very capable against real imaging missiles that are now in low-rate initial production. These use 128×128

IR and visible arrays. Jammers can make the problem worse, acting as a beacon. Flares are rejected due to track profile (objects that move away from the aircraft are ignored). Initial work with lasers to dazzle or saturate the imager will have some effect, but this may be countered by software changes in the missile's tracking algorithm. Laser-based IR jammers have been demonstrated in the lab and field with brassboard units and may be operationally deployed in five years.

Already in development are two color imaging systems, as well as hyperspectral systems. In these the sensor looks at the object at several wavelengths from UV to IR. Helicopters have a unique spectral signature when compared to flares, IR jammers, etc. The best way to counter is to use a medium-power laser to burn up the sensor's focal plane arrays. It will be a while before directed energy weapons (DEW) are on board transport helicopters.

We also note that no countermeasures exist for beamrider missiles such as the RBS 70, currently for sale on the world market.

We are not suggesting that the IR SAM problem is unsolvable. The technology to counter any IR missile can be developed. The key point is that historically it has been easier to modify offensive weapons than to develop new countermeasures. We should not assume that the enemy will let an IRCM system be effective against SAMs.

To generalize this point, we have observed a tendency in the FTR discussion for advocates to invoke various high-technology solutions to the survivability problem. As an example, one often-mentioned suggestion has been to install active defenses aboard the FTR using anti-aircraft (AA) gun technology. We contacted the two leading AA gun manufacturers, Oerlikon and Bofors. Oerlikon responded that "the feasibility to mount such a system on a helicopter for its own defence seems very low to us and, therefore, we have no interest in pursuing this."²

Bofors manufactures the AC-130 Spectre gunship's main gun. The company was interested in the concept, but RAND was the first to

²Telefax from Oerlikon, August 21, 2001.

inquire about this potential new application. We believe the development of “hard-kill” IR and RF SAM countermeasures is a critical element in the development of a survivable FTR or any aircraft that will fly in harm’s way.

The limited number of development activities for air defense countermeasures does not, however, support the vertical envelopment proponents’ claims for potential new ways of enhancing JTR survivability. We note that the current S&T plan has no active countermeasure component. It is risky to depend on other agencies to develop this critical technology.

Figure 21 illustrates that many key air defense assets are relatively inexpensive compared to the cost of transport aircraft. The chart shows a logarithmic plot of system costs and illustrates that low-altitude air defense systems are several orders of magnitude lower than transport costs. Long-range RF SAMs can have costs comparable to aircraft, but in the previous charts we illustrated cases where those SAMs are suppressed.

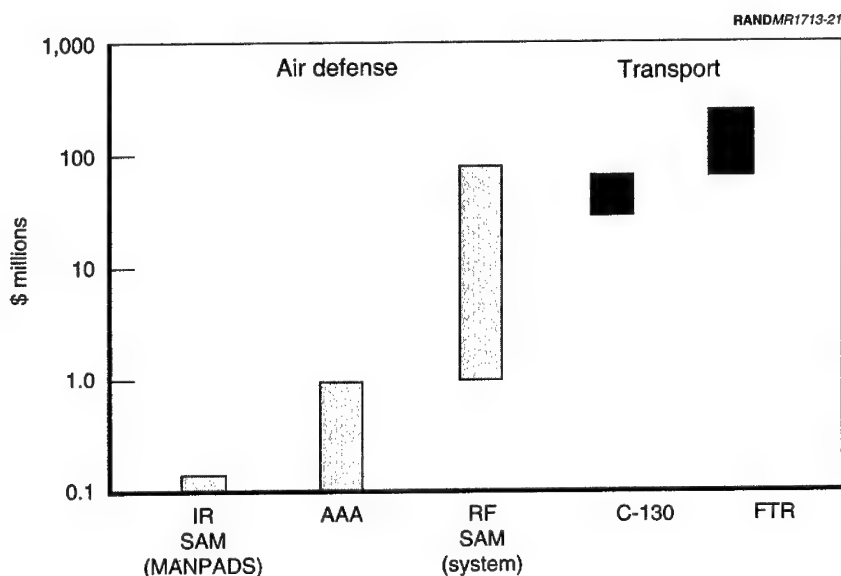


Figure 21—FTR and Air Defense Systems Costs

While it is reasonable to assume that the United States may be able to vastly outspend many Third World rivals, the cost ratios in the above chart indicate that the system cost imbalance may be so large that this may not be an important consideration. Costs for hand-held IR SAMs are as low as a few thousand dollars, and it is reasonable to assume that any rival will have a significant arsenal of these weapons. There are currently more than 500,000 IR SAMs deployed worldwide, most with current allies but some with former allies and/or current adversaries. IR SAMs can cost from around \$10,000 for the older models to \$100,000 for the current state-of-the-art missiles. The current (FY 2000) U.S. Army purchase price for a Stinger is around \$50,000. Anti-helicopter mines will cost around \$30,000 and represent another low-cost defense. If we invest in a large FTR fleet, it is reasonable to assume our adversaries would invest in anti-rotorcraft weaponry.

CHAPTER SUMMARY

We now summarize our survivability analysis. The FTR is a large, slow, and noisy (we have not modeled the acoustic signature) aircraft, and it is extremely vulnerable to a large number of low-cost, low-altitude threats such as guns, AAA, and MANPADS.

Technology improvements could allow the FTR to overcome many of the current SAM threats. We note, however, the history of IR and RF SAM countermeasures to lag a generation behind the missile seeker technology. If the FTR is to be survivable in the virtual envelopment concept, significant increases are needed in missile countermeasure development programs.

These arguments are not intended to exclude the potential of rotorcraft-facilitated vertical envelopment for the Objective Force. But they do imply that there will be significant operational constraints on the use of rotorcraft. Tiltrotors, with their ability to fly high above the low-cost, low-altitude threats, along with the Air Force's ability to suppress medium/long-range RF SAMs, significantly enhance FTR mission survivability. Of course, the requirement to land remains. Another option may be to evade defenses, though it is always difficult to find out the location of small weapons like MANPADS. Other options may involve clearing paths on the ground or considering smaller armored insertions with only a few

FTRs. Finally, there is the option of using the FTR to fly around the edges of the battlefield and avoid penetration runs that would expose the vehicle to significant enemy fire. In any event, the notion of multiple FTRs freely flying around the battlefield cannot be considered unless there are new developments in ensuring survivability.

POLICY IMPLICATIONS

In this chapter we consider the policy implications of the preceding analysis and identify strategies for the Army to continue to pursue the concept of vertical envelopment.

Figure 22 depicts the principal finding from the analysis: an FTR capable of carrying a lighter load, for a shorter distance, and around the edges of the battlefield may be more survivable and technically and financially feasible than an FTR aimed at fulfilling the nominal requirements. We also note that the military analysis of the vertical envelopment mission has not been carried out to such detail that these two concepts can be distinguished in terms of their impact on combat effectiveness. *It is too early for the Army to focus in on a single FTR concept. Prospective analyses should remain open to a wide range of options until there are compelling reasons to identify a single concept.*

It is also important to recognize that there is no compelling rationale for either the 20-ton lift or the 500-kilometer all-VTOL radius. The 20-ton number emerged from the Army's desire to ensure that the FCS could be transported aboard the C-130 and the mistaken assumption that 20 tons was a reasonable planning number for the C-130. The C-130 can only transport 20 tons under the most favorable conditions. It is more realistic to assume the C-130 is capable of carrying between 12 and 18 tons on a routine basis.¹

¹See Cassidy (2001) for a discussion of the lift limitations of the C-130.

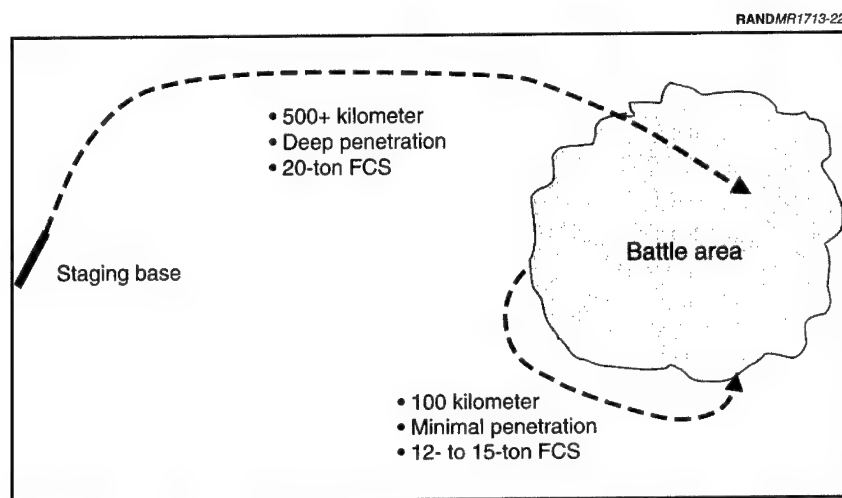


Figure 22—Two Vastly Different Versions of FTR

After payload, the most significant requirement is radius. The 500-kilometer radius results in significant demands for fuel efficiency and power, implying the need to develop innovative technology to compensate for the associated cost increase.

Is a 500-kilometer radius needed? Figure 23 highlights the entire transportation web for a deployment of the FCS from the home station to the battlefield. The schematic also highlights the circumstances in which a 500-kilometer, all-VTOL, radius would be needed.

Deploying FCS from home station requires ships or large transport aircraft like the C-17. C-17 capacity is a major concern, particularly given other deployment priorities that will limit Army use of the aircraft. In this regard, the Air Force's proposed C-5 fleet modernization could represent an important priority for the Army.

Once in an overseas staging area, the role of the FTR would depend on the relative location of the staging area, local airfields, and the battle site. It would also depend on the availability of C-130s and perhaps the Advanced Technology Transport, which is a paper design for an advanced aircraft capable of transporting FCS. The ATT is intended to land in farm fields at distances of 750 feet. However, if

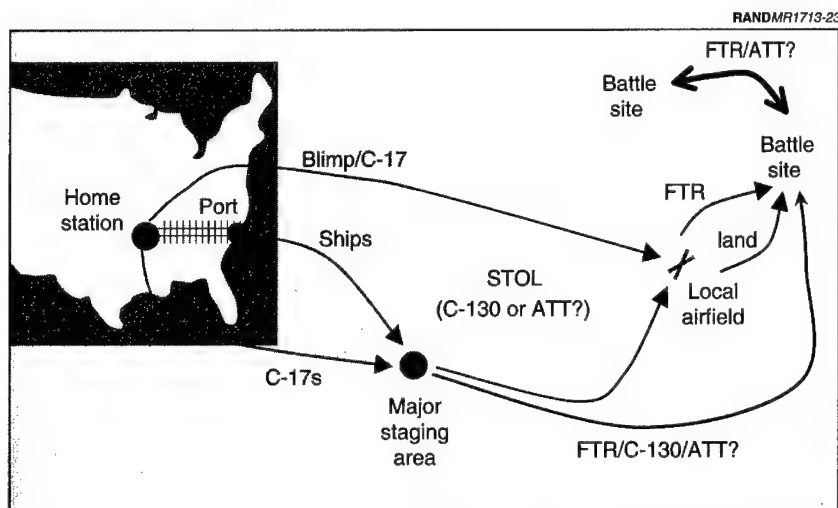


Figure 23—Is the FTR for Strategic Deployment?

the FTR were to depart directly from the staging area or a local airfield, it would not require an initial vertical takeoff or a final vertical landing.

The compelling case for an all-vertical capability is for movement within the battle site. However we have not yet seen scenarios in which 500-kilometer movements are essential. Five hundred kilometers is more typically a distance associated with strategic deployment. This kind of distance capability would be important if we view the FTR as part of the strategic deployment process, moving the FCS from rearward staging bases toward staging bases near the battle site.

There is obviously significant uncertainty as to the actual radius requirements for an FTR engaged in the vertical envelopment mission. As noted above, the actual need will depend on the interplay of various other assets under diverse scenarios. The Army has not yet performed a broad "systems" transportation study, so it is difficult to precisely define FTR needs. Such a study would seem to be a prerequisite for a more-precise definition of FTR requirements.

Figure 24 amplifies the issues of FTR range/radius needs by illustrating the vast overall payload capability of the C-130, the Air Force's

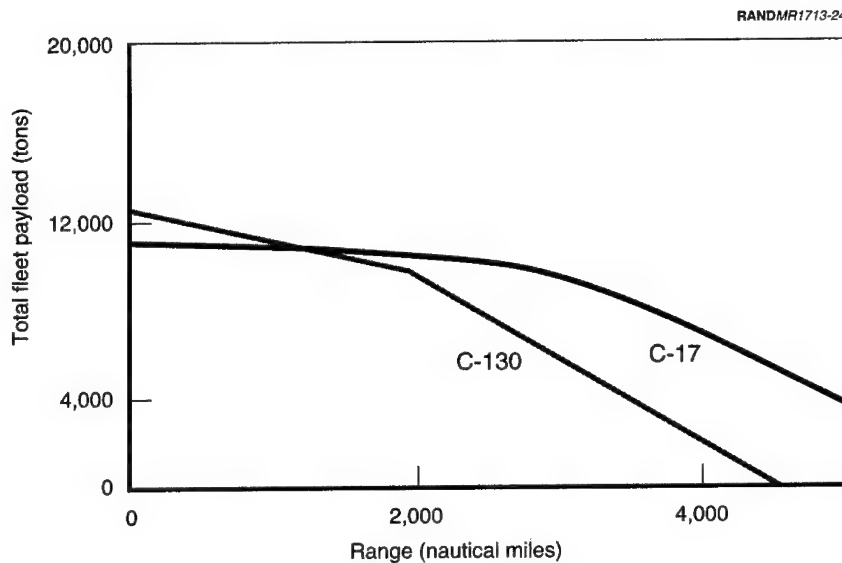


Figure 24—C-130 Fleet Offers Significant Short-Range Payload

midrange transport. While the C-17 and C-5 are typically viewed as the Air Force's heavy lifters, the greater number of C-130s implies that there is actually more C-130 capacity at short range than there is C-17 capacity. There are over 600 C-130 aircraft, and about 300–400 could be made available in a national emergency (roughly 200–300 C-130s are not configured as transports or are older models that would need modifications/extended maintenance to be able to transport a FCS combat vehicle).

Figure 24 suggests that the 500-kilometer range of the FTR might constitute an unnecessarily demanding requirement. There is ample C-130 capacity to bring the FCS to airfields near the battle site. The C-130 cannot provide vertical lift within the battle site, and it is for these shorter distances that the FTR might play a critical role. Reducing the FTR range/radius could have substantial benefits for lowering costs and simplifying technology requirements.

Table 1 highlights many of the variables the Army will need to consider before it can determine whether an FTR is needed and the specific performance parameters that it should fulfill.

Table 1
Unresolved Issues

- FCS weight
- FTR requirements/benefits in varied scenarios
 - Range
 - Survivability
- C-130/ATT as alternatives
- \$30–\$100 billion of other alternatives to:
 - Vertical envelopment (PGMs, UCAV, swarming)
 - FTR role in strategic deployment

Most obvious, but partially forgotten in the FTR policy discussion, has been its central role in FCS transportation and the need to design the FTR for the FCS weight. The programs should therefore be “joined at the hip,” but in fact the FCS is still only poorly defined, and moreover there has been little “crosstalk” between the programs. At this point, the single parameter of weight is the central linkage between the programs. As discussed above, the FTR community has assumed the FCS would weigh 20 tons because of the idealized C-130 capacity. The actual C-130 limitations may be a powerful force to lower the FCS maximum weight, while the need for ballistic protection of the vehicle could increase it. A firm understanding of FCS weight is essential before moving toward consideration of more detailed FTR design options.

There is also the need for additional combat modeling to better understand FTR survivability issues. We only looked at the effects on the FTR of various levels of air defenses. We did not investigate techniques (e.g., swarming) and technologies (e.g., UCAVs and decoys) that may have the potential to reduce or suppress the air defenses to the required levels. Lastly, there is a need to use additional combat modeling to better understand the military utility of FTR and vertical envelopment under significantly more varied scenarios.

Table 2 summarizes our findings from this study. As noted previously, computer battle modeling has shown significant advantages of

Table 2
Conclusions

- Modeling shows benefits for vertical envelopment, but there may be alternatives
- There is a clearly defined “knee in the curve” for each critical FTR rotorcraft development metric
 - Cost
 - Technology
 - Survivability
- Significant tradeoff space unexplored
- Too early to zero in on specific FTR design or FTR concept

the vertical envelopment concept, assuming that the FTR is survivable and can operate freely over the battlefield. However, this modeling is still preliminary and is not detailed enough to support the “nominal” parameters being used to size the FTR. We still do not know if a more limited FTR would provide the same utility and whether operational limitations aimed at improving survivability would erode the FTR’s value. We should also point out that the FTR has not been compared on an equal cost basis with other advanced technologies that might also improve the performance of the Objective Force.

The vertical envelopment concept is sufficiently attractive that the Army may want to continue to consider its feasibility, but it should realize that achievement of the nominal technical parameters is an ambitious and risky goal. To meet this goal in time for the FTR to be deployed with the Objective Force, the Army S&T community has proposed a technology development program that assumes the pace of progress will exceed historical patterns. We find little basis for this optimism.

The study sponsor asked us to find the “knee in the curve” in terms of critical FTR development issues. We found the knee in the curve for FTR cost, technical risk, and survivability. Modifying an existing heavy lift helicopter such as the CH-53E would mean a few hundred million dollars in development cost and result in an “FTR” unit cost

of less than \$40 million. The CH-53X would not meet the FTR nominal requirements but might have enough “battlefield utility” to be a relatively inexpensive implementation of the vertical envelopment concept. A new start would cost between \$10 billion and \$15 billion and FTR unit costs between \$100 million and \$150 million. The knee in the cost versus performance curve occurs, therefore, between modification of the CH-53E and new start.

Using NASA’s technology readiness levels, we found that helicopters have significantly less developmental risk than tiltrotors and that quad tiltrotor technology is not mature enough at present to warrant its consideration as a potential FTR design. We note that TRLs only evaluate program risk. They do not specify how long it will take to reduce risk to an appropriate level. Until critical subsystems for the quad tiltrotor have been demonstrated, its development risk is beyond the knee of the technology maturity versus performance curve.

The last curve we examined was survivability versus level of enemy air defense assets. Here the knee of the curve occurred between the different generations of currently deployed IR and RF SAMs and AAA. Given that the latest generations of SAMs and AAA are available on the world market, the survivability of an FTR will require that new countermeasures and/or new tactics, techniques, and procedures be developed and validated.

We recommend that the Army S&T community establish more modest goals and the operational community determine if achievement of those goals would allow development of a militarily useful system.

Thus our central conclusion is that there is still a significant unexplored tradeoff space and that it is too early to focus on a point design for FTR or even exclusively on a rotorcraft solution.

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THE FUTURE TRANSPORT ROTORCRAFT (FTR) is a proposed heavy-lift helicopter capable of transporting the Army's Future Combat System (FCS) family of combat vehicles. The authors review RAND Arroyo Center's analysis of the engineering, operational, and survivability risks and uncertainties associated with the FTR.

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